Early-universe constraints on dark energy

Rachel Bean
Theoretical Physics, The Blackett Laboratory, Imperial College, Prince Consort Road, London, United Kingdom

Steen H. Hansen and Alessandro Melchiorri
NAPL, University of Oxford, Keble Road, OX1 3RH Oxford, United Kingdom

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In the past years "quintessence" models have been considered which can produce the accelerated expansion in the universe suggested by recent astronomical observations. One of the key differences between quintessence and a cosmological constant is that the energy density in quintessence, Ω_ϕ, could be a significant fraction of the overall energy even in the early universe, while the cosmological constant will be dynamically relevant only at late times. We use standard big bang nucleosynthesis and the observed abundances of primordial nuclides to put constraints on Ω_ϕ at temperatures near $T \sim 1$ MeV. We point out that current experimental data do not support the presence of such a field, providing the strong constraint Ω_ϕ (MeV)<0.045 at 2σ C.L. and strengthening previous results. We also consider the effect a scaling field has on cosmic microwave background (CMB) anisotropies using the recent data from BOOMERANG and DASI combined with SNIa data, providing the CMB constraint $\Omega_\phi \leqslant 0.39$ at 2σ during the radiation dominated epoch.

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I. INTRODUCTION

Recent astronomical observations [1] suggest that the energy density of the universe is dominated by a dark energy component with negative pressure which causes the expansion rate of the universe to accelerate. One of the main goals for cosmology, and for fundamental physics, is ascertaining the nature of the dark energy [2].

In the past years scaling fields have been considered which can produce an accelerated expansion in the present epoch. The scaling field is known as "quintessence" and a vast category of "tracker" quintessence models have been created (see for example [3,4] and references therein), in which the field approaches an attractor solution at early times, with its energy density scaling as a fraction of the dominant component. The desired late time accelerated expansion behavior is then set up independently of initial conditions, with the quintessential field dominating the energy content.

Let us remind the reader of the two key differences between the general quintessential model and a cosmological constant: firstly, for quintessence, the equation-of-state parameter $w_\phi = p/\rho$ varies in time, usually approaching a present value $w_0 < -1/3$, while for the cosmological constant it remains fixed at $w_\Lambda = -1$. Secondly, during the attractor regime the energy density in quintessence Ω_ϕ is, in general, a significant fraction of the dominant component while Ω_Λ is only comparable to it at late times.

Future supernovae luminosity distance data, as might be obtained by the proposed Supernova Acceleration Probe (SNAP) satellite, will probably have the potential to discriminate between different dark energy theories [5]. These datasets will only be able to probe the late time behavior of the dark energy component at redshift $z < 2$, however. Furthermore, since the luminosity distance depends on w through a multiple integral relation, it will be difficult to infer a precise measurement of $w(z)$ from these datasets alone [6].

In this paper we take a different approach to the problem, focusing our attention on the early time behavior of the quintessence field, when the tracking regime is maintained in a wide class of models, and Ω_ϕ is a significant ($\geqslant 0.01$, say) fraction of the overall density.

In particular, we will use standard big bang nucleosynthesis (BBN) and the observed abundances of primordial nuclides to put constraints on the amplitude of Ω_ϕ at temperatures near $T \sim 1$ MeV. The inclusion of a scaling field increases the expansion rate of the universe, and changes the ratio of neutrons to protons at freeze-out and hence the predicted abundances of light elements.

The presence of this field in the radiation dominated regime also has important effects on the shape of the spectrum of the cosmic microwave background anisotropies. We use the recent anisotropy power spectrum data obtained by the BOOMERANG [7] and DASI [8] experiments to obtain further, independent constraints on Ω_ϕ during the radiation dominated epoch.

There are a wide variety of quintessential models; we limit our analysis to the most general ones, with attractor solutions established well before nucleosynthesis.

More specifically, we study a tracker model based on the exponential potential $V = V_0 e^{-\lambda\phi}$ [9]. If the dominant component scales as $\rho_n = \rho_0 (a_0/a)^n$, then the scaling field eventually approaches an attractor solution, and its fractional energy density is given by $\Omega_\phi = n/\lambda^2$. However, the pure exponential potential, since it simply mimics the scaling of the dominant matter in the attractor regime, cannot produce an accelerated expanding universe in the matter dominated epoch.

Therefore, we focus our attention on a recently proposed model by Albrecht and Skordis (referred to as the AS model hereafter) [10], motivated by physics in the low-energy limit of M theory, which includes a factor in front of the exponen-

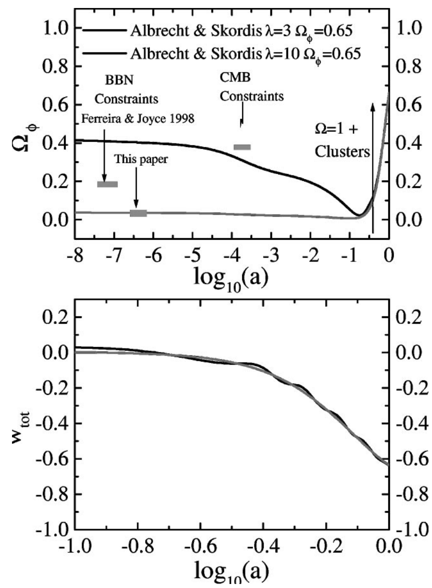

FIG. 1. Top panel: Time behavior of the fractional energy density Ω_ϕ for the Albrecht and Skordis model together with the constraints presented in the paper. The parameters of the models are (assuming $h=0.65$ and $\Omega_\phi=0.65$) $\lambda=3$, $\phi_0=87.09$, $A=0.01$ and $\lambda=10$, $\phi_0=25.82$, $A=0.01$. Bottom panel: Time behavior for the overall equation of state parameter w_{tot} for the two models. Luminosity distance data will not be useful in differentiating the two models.

tial, so that it takes the form $V=V_0[(\phi_0-\phi)^2+A]e^{-\lambda\phi}$. The prefactor introduces a small minimum in the potential. When the potential gets trapped in this minimum its kinetic energy disappears, triggering a period of accelerated expansion, which never ends if $A\lambda^2<1$ [11].

In Fig. 1 we introduce and summarize the main results of the paper. In the figure, the BBN constraints obtained in Sec. II, and the cosmic microwave background (CMB) constrains obtained in Sec. III are shown together with two different versions of the AS model which both satisfy the condition $\Omega_\phi=0.65$ today.

II. CONSTRAINTS FROM BBN

In the last few years important experimental progress has been made in the measurement of light element primordial abundances. For the ^{4}He mass fraction, $Y_{\rm He}$, two marginally compatible measurements have been obtained from regression against zero metallicity in blue compact galaxies. A low value $Y_{\rm He}=0.234\pm0.003$ [12] and a high one $Y_{\rm He}=0.244\pm0.002$ [13] give realistic bounds. We use the high value in our analysis; if one instead considered the low value, the bounds obtained would be even stronger.

Observations in different quasar absorption line systems give a relative abundance for deuterium, critical in fixing the baryon fraction, of $D/H=(3.0\pm0.4)\times10^{-5}$ [14]. Recently a new measurement of deuterium in the damped Lyman-α system was presented [15], leading to the weighted mean abundance $D/H=(2.2\pm0.2)\times10^{-5}$. We use the value from [14] in our analysis; the use of [15] leads to an even stronger bound.

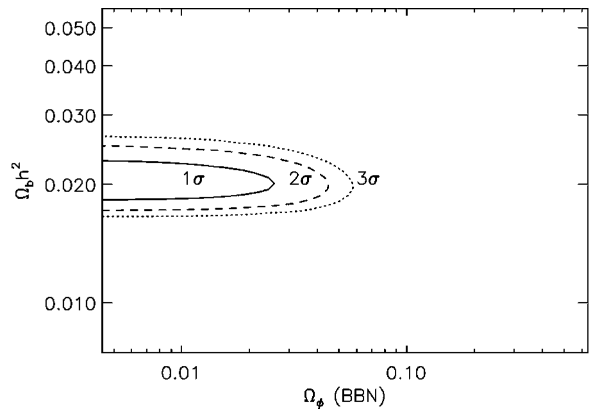

FIG. 2. 1, 2 and 3σ likelihood contours in the $(\Omega_b h^2,\Omega_\phi(1\ \mathrm{MeV}))$ parameter space derived from ^{4}He and D abundances.

In the standard BBN scenario, the primordial abundances are a function of the baryon density $\eta\sim\Omega_b h^2$ only. To constrain the energy density of a primordial field at $T\sim$MeV, we modified the standard BBN code [16], including the quintessence energy component Ω_ϕ. We then performed a likelihood analysis in the parameter space $(\Omega_b h^2,\Omega_\phi^{BBN})$ using the observed abundances $Y_{\rm He}$ and D/H. In Fig. 2 we plot the 1, 2 and 3σ likelihood contours in the $(\Omega_b h^2,\Omega_\phi^{BBN})$ plane.

Our main result is that the experimental data for ^{4}He and D do not favor the presence of a dark energy component, providing the strong constraint Ω_ϕ (MeV)<0.045 at 2σ (corresponding to $\lambda>9$ for the exponential potential scenario), strengthening significantly the previous limit of [17], Ω_ϕ (MeV)<0.2. The reason for the difference is due to the improvement in the measurements of the observed abundances, especially for the deuterium, which now corresponds to approximately $\Delta N_{\rm eff}<0.2-0.3$ additional effective neutrinos (see, e.g. [18]), whereas Ref. [17] used the conservative value $\Delta N_{\rm eff}<1.5$.

One could worry about the effect of any underestimated systematic errors, and we therefore multiplied the error-bars of the observed abundances by a factor of 2. Even taking this into account, there is still a strong constraint Ω_ϕ (MeV) <0.09 ($\lambda>6.5$) at 2σ.

III. CONSTRAINTS FROM CMB

The effects of a scaling field on the angular power spectrum of the CMB anisotropies are several [10]. Firstly, if the energy density in the scaling quintessence is significant during the radiation epoch, this would change the equality redshift and modify the structure of the peaks in the CMB spectrum (see e.g. [19]).

Secondly, since the inclusion of a scaling field changes the overall content in matter and energy, the angular diameter distance of the acoustic horizon size at recombination will change. This would result in a shift of the peak positions on the angular spectrum. It is important to note that this effect does not qualitatively add any new features additional to those produced by the presence of a cosmological constant [20].

Third, the time-varying Newtonian potential after decoupling will produce anisotropies at large angular scales through the integrated Sachs-Wolfe (ISW) effect. Again, this effect will be difficult to disentangle from the same effect generated by a cosmological constant, especially in view of the affect of cosmic variance and/or gravity waves on the large scale anisotropies.

Finally, the perturbations in the scaling field about the homogeneous solution will also slightly affect the baryon-photon fluid modifying the structure of the spectral peaks. However, this effect is generally negligible.

From these considerations, supported also by recent CMB analysis [21,22], we can conclude that the CMB anisotropies *alone* cannot give significant constraints on w_ϕ at late times. If, however, Ω_ϕ is significant during the radiation dominated epoch it would leave a characteristic imprint on the CMB spectrum. The CMB anisotropies can then provide a useful cross check on the bounds obtained from BBN.

One should keep in mind that Ω_ϕ could be significantly different at the time of BBN and CMB, e.g. if one considers decaying neutrino models (see e.g. discussion and references in [23]).

To obtain an upper bound on Ω_ϕ at last scattering, we perform a likelihood analysis on the recent BOOMERANG [7] and DASI [8] data. The anisotropy power spectrum from BOOMERANG and DASI was estimated in 19 bins between $l=75$ and $l=1025$ and in 9 bins, from $l=100$ to $l=864$ respectively. Our database of models is sampled as in [26], we include the effect of the beam uncertainties for the boomerang data, and we use the public available covariance matrix and window functions for the DASI experiment. There are naturally degeneracies between Ω_m and Ω_Λ which are broken by the inclusion of SNIa data [1]. It is worth pointing out that the inclusion of an age prior to the Universe of $\tau > 11$ gyr [24,25], and in particular the SNIa data improve the bound on Ω_ϕ [23].

By finding the remaining "nuisance" parameters which maximize the likelihood, we obtain $\Omega_\phi < 0.39$ at 2σ level during the radiation dominated epoch. Therefore, while there is no evidence from the CMB anisotropies for the presence of a scaling field in the radiation dominated regime, the bounds obtained are actually larger than those from BBN.

In Fig. 3 we plot the CMB power spectra for 2 alternative scenarios. The CMB spectrum for the model which satisfies the BBN constraints is practically indistinguishable from the spectrum obtained with a cosmological constant, and 3.04 effective neutrino degrees of freedom. Nonetheless, if the dark energy component during radiation is significant, the change in the redshift of equality leaves a characteristic imprint in the CMB spectrum, breaking the geometrical degeneracy. This is also found when considering non-minimally coupled scalar fields [27], even when the scalar is a small fraction of the energy density at last scattering. In the minimally coupled models considered here, this is equivalent to an increase in the neutrino effective number, i.e. altering the number of relativistic degrees of freedom at last scattering.

In Fig. 4 we have plotted the corresponding matter power spectra together with the decorrelated data points of Ref. [28]. As one can see, the model with $\lambda=3$ seems in disagreement with the data, producing less power than the model with $\lambda=10$, with this last one still mimicking a cosmological constant. The less power can still be explained by the increment in the radiation energy component which shifts the equality at late time and the position of the turn-around in the matter spectrum towards larger scales. A bias factor could in principle solve the discrepancy between the $\lambda=3$ model and

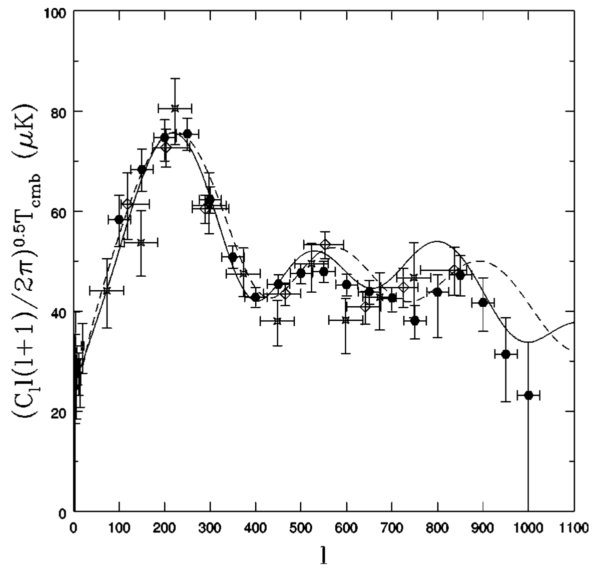

FIG. 3. CMB anisotropy power spectra for the Albrecht-Skordis models with $\lambda=10$, $\phi_0=25.82$ and $A=0.01$ (full line) and $\lambda=3$, $\phi_0=87.09$ and $A=0.01$ (dashed line), both with $\Omega_\phi=0.65$ and $h=0.65$, are plotted against data points from BOOMERANG (hexagons), MAXIMA (crosses) and DASI (diamonds).

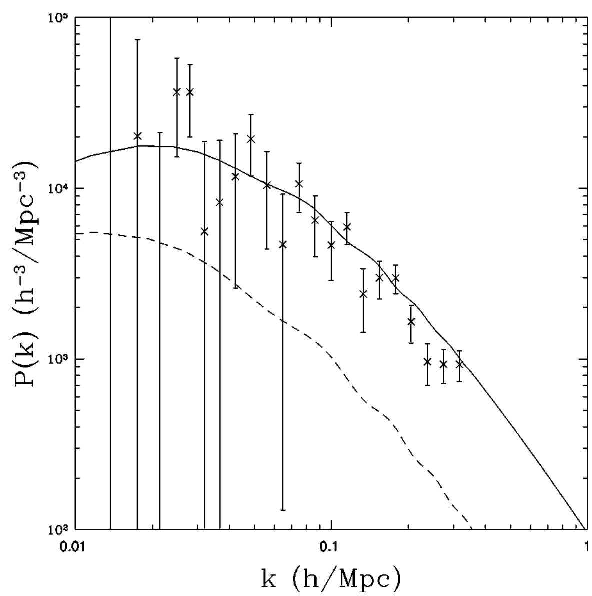

FIG. 4. Matter power spectra for the 2 models in Fig. 3. The predictions support those in the CMB spectra, the quintessence model in agreement with BBN with $\lambda=10$ (full line) is in good agreement with observations (the decorrelated data of Hamilton et al.) whilst the model with $\lambda=3$ (short dash) seems in clear disagreement.

the data, however, the matter fluctuations over a sphere of size $8h^{-1}$ Mpc are $\sigma_8 \sim 0.5$ to be compared with the observed value $\sigma_8 = 0.56\Omega_m^{-0.47} \sim 0.9$ [29]. With the unsettled question of bias, the large scale structure (LSS) data do not seem competitive at the moment, however, better understanding of the bias, or weak lensing observations [30] may open up further opportunities to constrain quintessence models even more tightly through the matter power spectrum.

IV. CONCLUSIONS

We have examined BBN abundances and CMB anisotropies in a cosmological scenario with a scaling field. We have quantitatively discussed how large values of the fractional density in the scaling field Ω_ϕ at $T \sim 1$ MeV can be in agreement with the observed values of ^{4}He and D, assuming standard big bang nucleosynthesis. The 2σ limit $\Omega_\phi(1\ \mathrm{MeV}) < 0.045$ severely constrains a wide class of quintessential scenarios, like those based on an exponential potential. For example, for the pure exponential potential the total energy today is restricted to $\Omega_\phi = \frac{3}{4}\Omega_\phi(1\ \mathrm{MeV}) \leqslant 0.034$. Our 2σ limit on the λ parameter, could also place useful constraints on other dark energy models. In the case of the Albrecht-Skordis model, for example, combining our result with the condition $A\lambda^2 \leqslant 1$, one finds that $A < 0.01$ in order to have an eternal acceleration. Furthermore, if we want to have $\Omega_\phi \geqslant 0.65$, then one must have $\phi_0 < 29$.

As mentioned earlier, our BBN constraint is limited to models assuming standard big bang nucleosynthesis, where the scaling field simply adds energy density to the expanding universe.

The bound on Ω_ϕ (MeV) can be also weakened by introducing new physics which might change the electron neutrino distribution function. Such distortions will alter the neutron-proton reactions, and subsequently the final abundances. Such new physics could take the form of heavy decaying neutrinos, or light electron neutrinos oscillating with a sterile species, both of which can lead to fewer effective degrees of freedom (see e.g. [31,32] and references therein).

There are several quintessence models which evade the BBN bound, and let us mention a few. The simplest way is to modify the standard model of reheating in order to have late-entry of the field in the attractor solution, after BBN [17]. In the "tracking oscillating energy" of Ref. [33] one can choose parameters which both let Ω_ϕ be small at BBN times and big today. However, since the probability of the randomly selected parameters decreases rapidly for stronger BBN constraints, this model may not appear too natural (in the language of [33]). Another class of models which evade the BBN bound are the models exhibiting kination at early times. This means that Ω_ϕ is suppressed at early times, taking a value well below that made by the BBN constraint [11].

All these models are compatible with our 1σ constraint obtained from CMB data but they nonetheless leave a characteristic imprint on CMB and also large scale structure. It is therefore expected that future data from satellite experiments such as the Microwave Anisotropy Probe (MAP) or Planck, and measurements of the matter power spectrum using weak lensing and the Digital SLOAN survey will enable tighter limits to be placed on the presence of a scalar quintessence field in the early universe.

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